THE FREQUENCY DEPENDENCE OF AQUIFER-SYSTEM ELASTIC STORAGE COEFFICIENTS: IMPLICATIONS FOR ESTIMATES OF AQUIFER HYDRAULIC PROPERTIES AND AQUIFER-SYSTEM COMPACTION

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Aquifer-system compaction resulting from reduced fluid pressures in interbedded alluvial aquifers is governed by the skeletal elastic storage coefficients of the aquifer, S_{ke}, and the interbeds, S'_{ke}, and the inelastic storage coefficient of the aquifer system, S^*_{kv}. The elastic skeletal components are related by:

$$S^*_{ke} = S_{ke} + S'_{ke},$$

where S^*_{ke} is the skeletal elastic storage coefficient of the aquifer system. Where measurements of aquifer-system compaction and aquifer fluid pressures are available, stress-strain diagrams (for example, see Carpenter abstract where stress-displacement diagrams are presented for horizontal movement across an earth fissure in the Picacho Basin, Arizona) can be computed and estimates of S^*_{ke} and S^*_{kv} can be obtained (Riley, 1969). Typically, this stress-strain relation is developed from the seasonal drawdown and recovery cycle associated with agricultural and municipal/industrial ground-water use. As such, the aquifer system storage estimates are representative of long period, low frequency responses of the aquifer system to stresses. Estimates of S'_{ke} are computed from S^*_{ke} and S_{ke}, where by contrast, estimates of S_{ke} are often obtained on the basis of short duration, high frequency responses of aquifer fluid pressures measured in wells to imposed hydraulic stresses, such as a pumping test or slug test. This approach for computing S'_{ke} may not be valid if the aquifer-system response to stress is dependent on the frequency of the imposed stress (Helm, 1974). The discussion that follows addresses only the elastic range of aquifer-system compaction.

For uncemented granular material the barometric efficiency of a well/aquifer system is inversely proportional to S, the aquifer storage coefficient (Jacob, 1940), and so the frequency response of barometric efficiency to atmospheric loading can serve to illustrate the relation between the elastic properties of the aquifer and the frequency of the applied load (fig. 1). The theoretical response (Quilty and Roeloffs, 1991) is computed for a 150-m-thick, partially confined aquifer, hydraulically connected to a water table 50 m below land surface through a specified vertical hydraulic diffusivity, D_v. For values of D_v typical of interbedded alluvial aquifer systems, between 1.0 x 10^2 and 1.0 x 10^4 m^2/d, the response is frequency dependent for frequencies less than about 0.1 and 10 cycles per day, respectively. The frequency-dependent part of these curves represents the influence of fluid flow and drainage of the aquifer system in response to a change in the atmospheric load. For small values of D_v, 1.0 m^2/d, characteristic of a confining unit, the response is frequency-independent for stress frequencies greater than 0.001 cycles per day. The frequency-independent part of these curves is known as the static-confined response and represents the mechanical, undrained response of the aquifer to loading.

This general relation between the decrease in barometric efficiency for lower frequencies of the applied load suggests that estimates of S^*_{ke} based on the cyclic annual recovery limb of a stress-strain diagram, with a frequency of 2.74 x 10^{-3} cycles per day (1 cycle/year), would be overestimated with regard to the aquifer-system confined response for a wide range of D_v. When used with estimates of S_{ke} derived from aquifer tests typically conducted at higher frequencies (over a period of hours to days), and more likely representative of the undrained aquifer-system confined response, the resultant estimates of S'_{ke} would also be overestimated. This approach for computing S'_{ke} leads to overestimation of the magnitude of aquifer-system rebound during the recovery cycle.

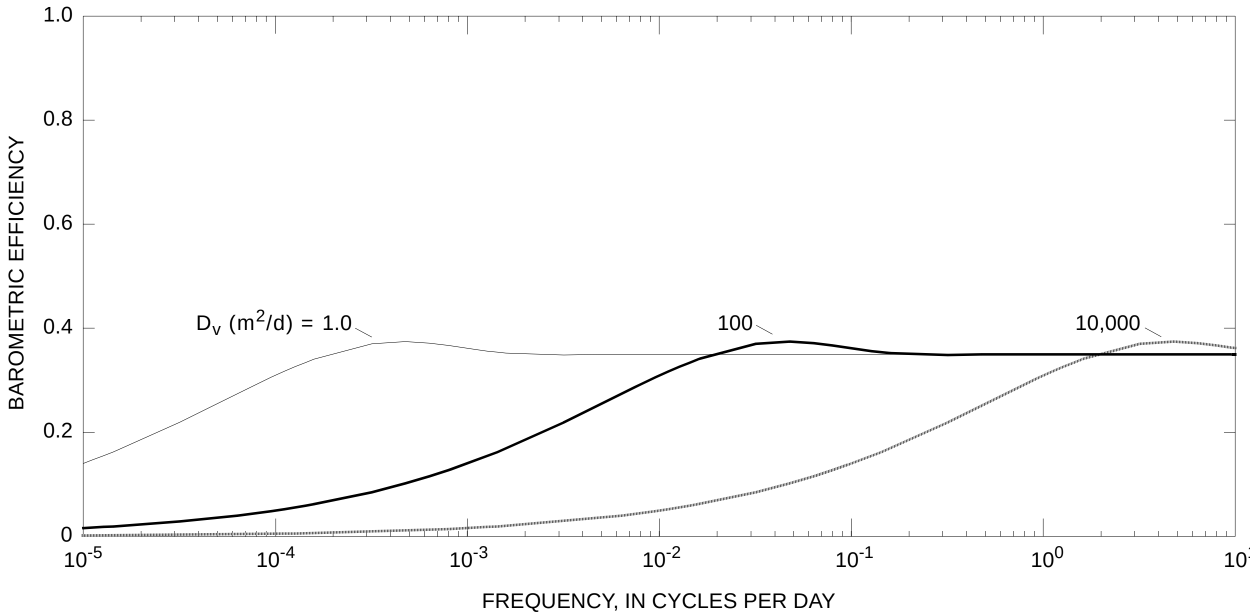

Figure 1. Theoretical response of the barometric efficiency of a well /aquifer to atmospheric loading. Barometric efficiency is plotted as a function of the frequency of the applied load, and the vertical hydraulic diffusivity, D_v. The static-confined barometric efficiency is 0.35.

Measurement and analytical techniques can be employed to compute the well/aquifer system frequency response to atmospheric loading (Rojstaczer, 1988; Quilty and Roeloffs, 1991), although information at frequencies less than about 0.05 cycles per day is difficult to obtain due to instrument drift and the required length of the barometric pressure and aquifer fluid pressure time series. Characteristics of the frequency response can be determined for higher frequencies that may reveal a frequency-dependent response from which estimates of D_v can be determined on the basis of the best fit to the theoretical response. If earth tides can also be measured, estimates of aquifer elastic skeletal specific storage, Ss_{ke}, and porosity, Φ, may also be computed (Bredehoeft, 1967; Rojstaczer and Agnew, 1989), where

$$Ss_{ke} = S_{ke}/b,$$

and b is the thickness of the aquifer. For these reasons it is useful to evaluate the potential for measuring barometric efficiency and the aquifer-system response to earth tides in alluvial aquifers with aquifer-system compaction.

The relation between Ss_{ke} and barometric efficiency (fig. 2) and Ss_{ke} and the tidal areal strain sensitivity (fig. 3) can be determined when *a priori* estimates of Poisson's ratio, ν, and the solid grain compressibility of the aquifer, β_s, are known or can be estimated (Rojstaczer and Agnew, 1989). The areal strain sensitivity is the ratio of the aquifer fluid-pressure response measured as the open water-level fluctuation in a well to the imposed areal strain of the solid earth tide in parts per million. For the range of Ss_{ke}, 1.0 x 10^{-6} to 1.0 x 10^{-5} m^{-1}, representative of alluvial aquifers where aquifer-system compaction has been measured (Ireland and others, 1984; Hanson, 1989), the barometric efficiency and the areal strain sensitivity are strongly dependent on Φ, especially near the lower end of the range. Larger barometric efficiencies occur with relatively small values of Ss_{ke}, and large values of Φ. Larger areal strain sensitivities similarly occur with relatively small values of Ss_{ke}, but unlike for atmospheric loading, small values of Φ. For midrange values of Ss_{ke} and Φ, barometric efficiencies between 0.1 and 0.5, and areal strain sensitivities between 0.2 and 0.5 m/microstrain could be expected.

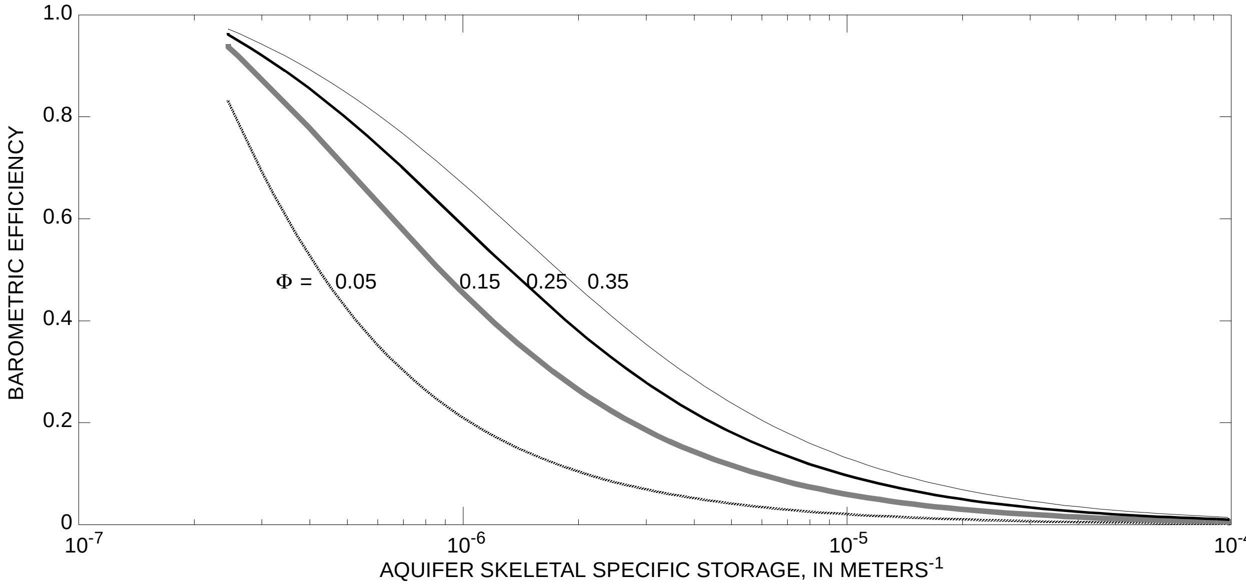

Figure 2. Barometric efficiency of a well/aquifer under static-confined conditions as a function of the aquifer skeletal specific storage, Ss_{ke}, and aquifer porosity, Φ. The compressibility of the solid grains, β_s, is 2.0×10^{-11} Pa^{-1} and Poisson's ratio, ν, is 0.25.

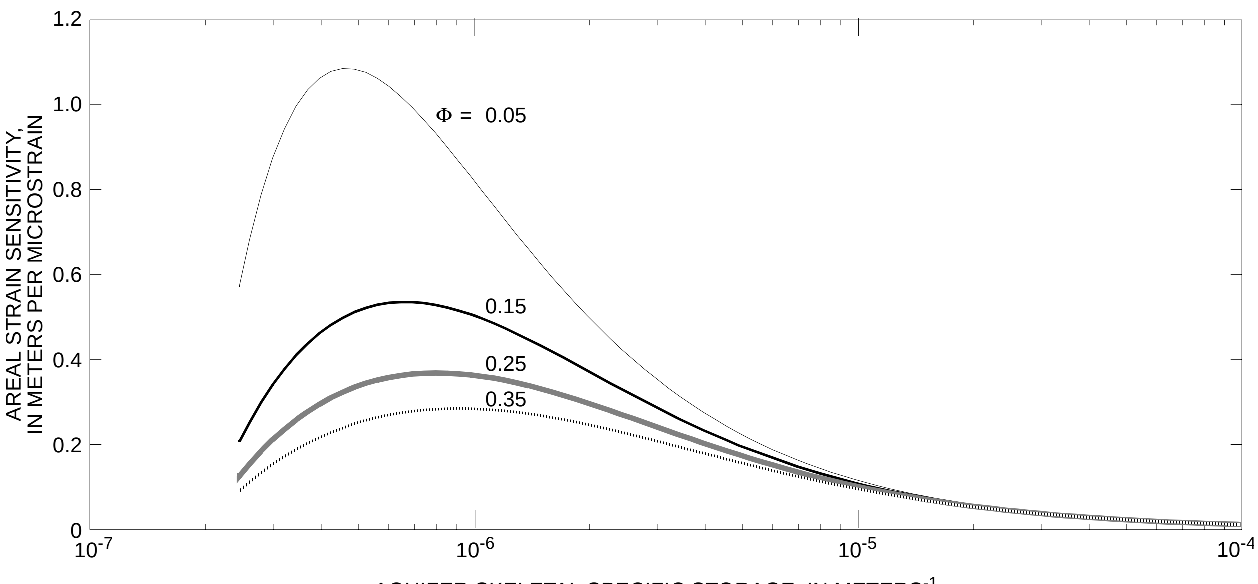

Figure 3. Sensitivity of an aquifer to areal strain under static-confined conditions as a function of the aquifer skeletal specific storage, Ss_{ke}, and aquifer porosity, Φ. The compressibility of the solid grains, β_s, is 2.0×10^{-11} Pa^{-1} and Poisson's ratio, ν, is 0.25.

Diurnal and semidiurnal fluctuations in barometric pressure at land surface typically comprise the smallest cyclical changes in barometric pressure and occur in the range of 0.02 to 0.03 m (equivalent height of water). A well with a static-confined barometric efficiency of 0.1 would produce a static-confined water-level fluctuation of about 0.002 to 0.003 m. A well with a static-confined areal strain sensitivity of 0.2 m/microstrain, responding to an areal strain of 0.012 microstrain (typical of the O_1 tide, the smaller of the two principal lunar tides), would produce a static-confined water-level change of about 0.0024 m. These conservative estimates of the well responses represent measurable water-level fluctuations attainable with widely available submersible pressure transducers and recording data loggers capable of resolving 0.00075 m of water-level change.

Within the range of expected hydraulic properties of alluvial aquifers where compaction is occurring, it is likely that the frequency response of an aquifer system to atmospheric loading and the sensitivity of the areal strain of an aquifer to earth tides can be determined. These responses can provide insight into the frequency dependence of the skeletal elastic storage coefficients, as well as provide estimates of aquifer hydraulic properties including Ss_{ke}, Φ, and D_v.